THE UNIVERSITY OF MIAMI

TIDAL FLUCTUATIONS OF THE FLORIDA CURRENT

BY

John Alan Smith

A THESIS

Submitted to the Faculty
of the University of Miami
in partial fulfillment of the requirements
for the degree of Master of Science

Coral Gables, Florida

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Subject

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Florida Current

John Alan Smith

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SMITH, JOHN ALAN (M.S. Physical Oceanography)

Tidal Fluctuations of the Florida Current. (July, 1968). Abstract of a Master's Thesis at the University of Miami. Thesis supervised by Professor Saul Broida.

This thesis is an examination of the short period fluctuations of tidal nature of the Florida Current surface flow from an analysis of direct surface current measurements made over a period of about a month in the Florida Straits during the latter portion of 1965. The principal conclusion reached is that the surface current is modulated by a diurnal standing wave, coupling the tides of the Atlantic Ocean with those of the Gulf of Mexico, which produces a pronounced diurnal effect on the surface current fluctuation.

ACKNOWLEDGMENTS

This work started as a result of the interest of myself as a career Naval Officer in the procedure employed for predicting tides, and terminated with an analysis of the fluctuations of tidal influence in the Florida Current. The end is really only the beginning. I sincerely hope that others will follow, as many have preceded, in continued research of all of the fluctuations of this important current.

The author is indebted to a multitude of persons for their assistance and patience during the preparation of this thesis. I am grateful to the members of my thesis committee, Drs. S. Broida, C. Rooth, R. Snyder, and D. Moore; in particular I wish to express my appreciation to Bernard Zetler, director of the E.S.S.A. Physical Oceanography Laboratory at Miami who served as my thesis committee co-chairman, without whose patient guidance and tireless enthusiasm I could not have completed this work.

I also wish to acknowledge the excellent cooperation and assistance provided by R. A. Cummings, C. B. Taylor and other Coast and Geodetic Survey personnel in Rockville, Maryland for providing tidal predictions and analysis; to General Dynamics and Dr. W. S. Richardson of Nova University for making available the Florida Current data; and, to my friend and classmate, Joseph Paletta, USN, for continued encouragement throughout this period.

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John Alan Smith
Lt., U.S. Navy

Coral Gables, Florida

July, 1968.

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1. INTRODUCTION

The pulsation of marine currents has long been a topic of major interest in the field of physical oceanography. Much of the dynamics of oceanic circulation can only be understood in terms of the velocity field and the forces acting upon it. In general, the study of current fluctuations is best considered on the basis of information concerning current velocities. Unfortunately, reliable information of this type has not been available in the past because of the inherent difficulties and expense involved in the gathering of such data. Numerous analyses of oceanic current fluctuations have of necessity been made on data over short duration periods, non-synoptic surveys, or resorted to the indirect measurement from dynamic computations. Conclusions based upon such information have often been highly speculative in regard to current fluctuations, although in many cases commendably accurate.

Improved technology in the field of ocean measurement instrumentation has made possible the collection of data over sufficient time intervals to provide meaningful results. The development of moored buoy systems in conjunction with dependable current recorders has provided a powerful tool which now permits us to commence directly examining the variation of ocean currents over long periods of time. The purpose of this paper is to examine the nature of current velocity fluctuations in the Florida Current using current speed measurements collected over a period of about a month at hourly intervals in the Straits of Florida from a moored buoy. Short period variations of tidal period will be

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investigated as a step towards the ultimate goal of long period fluctuation studies from which perhaps someday accurate predictions and forecasting of the Gulf Stream System and its associated effect on climate may be gained. It is evident that our knowledge of long-period variations will remain unsatisfactory until the short-period oscillations have been sufficiently described and explained.

II. HISTORY

The pulsations of tidal origin of the Florida Current have long been a subject of interest and speculation. As early as the mid 1800's, Pillsbury on BLAKE undertook the admirable task of occupying six anchor stations between Fowey Rocks, Florida and Gun Cay, Bahama Islands, devoting over 1100 hours in observing the Florida Current at this section in the course of two summers (Pillsbury, 1891). The longest continuous anchorage was for a period of 166 hours. He found monthly variations related to the declination of the moon and daily oscillations of tidal origin in the Florida Current, the latter amounting in some instances to a variation as large as 128 cm/sec. He reported two periods of increase and two periods of decrease in the Florida Current speed during the period of a lunar day.

In April 1937, Parr anchored ATLANTIS for a series of five hydrographic stations which were successively occupied for twenty-four hour periods in the Straits of Florida between Fowey Rocks and Gun Cay (Parr, 1937). He reported from analyzing hourly surface current speeds that there was up to a 50 cm/sec fluctuation of the speed of the Florida Current that was apparently caused by tidal forces. He found both diurnal and semidiurnal variations with the latter predominant.

From May 1950 to May 1951 the U.S. Navy Hydrographic Office recorded hourly Loran fixes from oil tankers traveling between Cape Hatteras and the Key West vicinity. From an analysis of over 5000 observations, it was concluded that there was an apparent tidal perio-

dicity in the surface current flow (O'Hare _et al_, 1953). An attempt was made to screen the tanker survey data for a semidiurnal tidal periodicity, but the results obtained were inconclusive.

In 1951 Murray attempted to analyze velocity fluctuations in the Florida Current by making numerous crossings between Miami and Gun Cay utilizing the Geomagnetic Electrokinetograph (GEK) (Murray, 1952). He was unable to detect any apparent periodicity in the fluctuations of the Florida Current, but pointed out the inherent difficulties involved with attempting to observe periodicities from scattered GEK observations.

From December 1952 to November 1953, GEK fix stations were occupied between the Miami Sea Buoy and Gun Cay. An attempt was made to study tidal fluctuations in the Florida Current by plotting 187 GEK measurements against time (Hela and Wagner, 1953). The data seemed to indicate the existence of a tidal fluctuation, although the fluctuations were strongly masked by non-tidal effects.

From studies of electric potential measurements between Key West, Florida and Havana, Cuba, Wertheim was able to show evidence of the diurnal tidal influence in the transport through the Florida Straits (Wertheim, 1954). He found that the ratio of the amplitudes of the harmonic coefficients for the tidal components M_2, S_2, K_1 and O_1 were in between those of the semidiurnal Atlantic tide at Miami and the diurnal Gulf of Mexico tide at Galveston, confirming the dependence of the transport on both tidal systems.

Webster analyzed a large amount of GEK data for both the Straits of Florida and off Onslow Bay, North Carolina. He concluded that although it was probably rash to ascribe the velocity fluctuation of the Florida Current predominantly to tidal causes, the periods of the

fluctuations observed were in the order of one day (Webster, 1961).

Recently Schmitz and Richardson utilized a least square harmonic analysis on transport data acquired over a period of three years using the free instrument technique across a section of the Florida Current (Schmitz and Richardson, 1967). Based on the limited data available, they indicate that it is possible that fluctuations of tidal period are the major modulation of the Florida Current transport. Their estimates of tidal coefficients for transport amplitudes are 3.5 ± 1 ($10^6 M.^3$ Sec^{-1}) for M_2, O_1 and K_1, and 1.5 ($10^6 M.^3$ sec^{-1}) for S_2.

III. EXPERIMENTAL PROCEDURE

GENERAL

During the latter portion of 1965 a General Dynamics ocean buoy was moored for testing and evaluation in the Straits of Florida at a location as shown in Figure 1. From the period November 20 to December 18, 1965, the buoy was equipped with a rotary current meter placed immediately beneath the water surface, installed by Dr. William Richardson. Current speed data for one minute averages taken approximately each hour were telemetered to the mainland and recorded. Also available for this period are wind speed, wind direction, barometric pressure and the significant wave height at the time of recording. Current direction is considered as essentially steady in the North-South orientation of the Florida Current at this location. A plot of current velocity versus time is illustrated by Figure 2.

Cursory examination of Figure 2 reveals fluctuations of current speed in the order of 30 cm/sec with apparent periodicity. Since the periodicity appears to be largely on the order of 24 hours and can be initially presumed to be due to tidal effects, it was decided to conduct a harmonic analysis on the data to determine if the fluctuations were indeed due largely to the tidal effects.

A. HARMONIC ANALYSIS OF TIDAL CURRENTS

Harmonic analysis is a method for describing periodic phenomena in which values of the dependent variable repeat themselves at equal intervals of time. The first practical application of harmonic analysis

Figure 1. General Dynamics Monster Buoy Location


MONSTER BUOY
LAT 26° 01'N
LONG 79° 51.2'W
C.&G.S. 1112
(CONTINUED ON CHART 1002)
(CONTINUED 30' ON CHART 1002)
Boynton Beach
Boca Raton
Great Isaac
North Bimini
South Bimini
Gun Cay
N Cat Cay
Victory Cays
Triumph Reef
Pacific Reef
FOWEY ROCKS
Indian Cay
Wood Cay
Settlement Pt

Figure 2. Current Velocity versus Time for the Period 21 November through 17 December 1965 in the Florida Current.

Figure 2. Current Velocity versus Time

is attributed to Lord Kelvin who in 1867 devised a method of reducing tidal height observations to harmonic constituents (Darwin, 1898).

The harmonic analysis of tidal currents or of currents having tidal components is a process by which the tidal components having relations to astronomical conditions are separated into elementary harmonic components or constituents. Each constituent represents a cyclical change during a particular period calculated from astronomical data. The constituents are in reality a substitution of hypothetical tide-producing satellites (having either fixed circular or elliptical orbits around the earth parallel to the equator) for the actual tide-producers, the moon and the sun.

Theoretically, there are a large number of tidal constituents needed to accurately resolve the complicated motions of the moon and the sun into simple components. Generally, however, in any given location most of these are of small amplitude, and all but a few may be disregarded for practical purposes. The major constituents used to determine the principal features of tidal currents are listed in Table 1 along with their respective periods. Although the amplitudes and phases of the tidal constituents are modified by local causes, the period of the constituents is defined by the configuration and periodic relative motions of the earth-sun-moon system, and is invariable. In order to determine the tidal constituents listed in Table 1, observations over a complete period of about fifteen days are required to separate the individual diurnal and semidiurnal constituents with a fair degree of accuracy. It has been proposed that extremely accurate measurements coupled with an extremely low noise level would permit the analysis of shorter periods (Munk and Hasselman, 1965), but such data

Table 1. Principal Tidal Constituents

TABLE 1

Principal tidal constituents

SEMIDIURNAL CONSTITUENTS	DESCRIPTION	SPEED (per solar hour)	PERIOD (Hrs.)
M_2	PRINCIPAL LUNAR--Has nearly the same mass as the real moon and moves in a circular orbit around the equator.	28.98°	12.42
S_2	PRINCIPAL SOLAR--Bears the same relationship to the real sun that M_2 bears to the real moon.	30.00°	12.00
N_2	LARGER LUNAR ELLIPTIC--Simulates the changing lunar tractive force from apogee to perigee.	28.44°	12.66
DIURNAL CONSTITUENTS			
K_1	LUNAR-SOLAR ELLIPTIC--Represents the lunar-solar diurnal tractive force.	15.04°	23.93
O_1	PRINCIPAL LUNAR--Represents the principal variation in the lunar diurnal tractive force.	13.94°	25.82

Note: M_2 and S_2 are in phase each 14.8 days at full moon and new moon producing spring tides, and in opposition when the moon is at first or last quarter producing neap tides. K_1 and O_1 are in phase each 13.7 days when the moon is at extreme north or south declination, and in opposition when the moon is over the equator. N_2 is in phase with M_2 each 27.6 days at perigee, and in opposition when at apogee.

is not as yet available for the Florida Current.

The harmonic constants sought for each of the major tidal constituents are amplitude and phase lag. Once determined, the constituents are then recombined and the resultant is the predicted tidal component of the current.

Mathematically in tidal current analysis, a finite trigonometric sum is fitted to a set of current data in which there is a partial tidal periodicity. A finite number of points will exist since the current data will exist only at discrete points. Therefore, the data may be fitted by a finite number of sine and cosine curves. Solving for the five constituents in Table 1, this can be represented by

$$Z_{(t)} = Z_{(o)} + \sum_{n=1}^{5} [a_n \text{Sin } W_n t + b_n \text{COS} w_n t] + R_m \qquad (1)$$

where

$Z_{(t)}$ = periodic variate with time. (eg. current velocity),

$Z_{(o)}$ = mean value of the variate,

n = the identification of the tidal constituent in equation (1),

W_n = the angular velocity of the n^{th} constituent ($W_n = \frac{2\pi}{T}$ where T is the period of the constituent),

t = time,

a_n and b_n = Fourier coefficients for each constituent,

and R_m = the residual

The harmonic Fourier coefficients for the series are solved from

$$a_n = \frac{2}{N} \sum_{k=1}^{N} Z_{(t)} \text{ Sin } W_n t_k \qquad (2)$$

and

$$b_n = \frac{2}{N} \sum_{k=1}^{N} Z_{(t)} \text{ COS } W_n t_k \qquad (3)$$

where

t_k = discrete points in time at which the data was collected,

and N = the total number of data points.

It is convenient to combine the sines and cosines of equation (1) which belong to the same n^{th} constituent (Gerges, 1966) into a single term

$$A_n \text{ Sin } (W_n t_k + \emptyset n)$$

yielding

$$Z_{(t)} = Z_o + \sum_{n=1}^{5} A_n \text{ Sin } (W_n t_k + \emptyset n) \qquad (4)$$

where

$$A_n = [a_n{}^2 + b_n{}^2]^{\frac{1}{2}}$$

and $\emptyset n = -\arctan \frac{an}{b_n}$.

A_n is called the amplitude and $\emptyset_n$ the phase of the n^{th} constituent.

In tidal analysis, A_n of the major tidal constituents is corrected by a node factor which compensates for the effects of the variation in the moon's node in each 18.6 year cycle, and is also corrected for interference effects in the analysis from other constituents. These include significant lesser constituents which sometimes may not be resolved from the actual data because of the length of the data series, but which may be inferred from the solved constituents. This is permitted by the fact that although the amplitude and phases of the tidal constituents at any location differ considerably from their theoretical equilibrium theory values, amplitudes and phases of the constituents of nearby frequencies at any place have relations that, in general, agree fairly closely with the relations of their theoretical coefficients. (Schureman, 1941).

$\emptyset_n$ is corrected for equilibrium arguments for starting times (to Zeta) in accordance with astronomical stages, and likewise corrected for interference effects from other tidal constituents to (Kappa).

There are a variety of methods available for solving for the tidal constituents. In the classical form of tidal analysis, a series of current observations is divided into periods equal to the known period of each individual tidal constituent. Each period is then further sub-divided into a number of equal parts called the constituent hours which are numbered consecutively starting with zero at the initial instant for each period. Thus, the phase of each constituent and its overtides (harmonics) will be the same for a fixed instant in all sub-divisions having the same number, but all other constituents will have different phases (Dronkers, 1961). By summing and averaging all velocities which are observed at a fixed instant in each sub-interval (constituent hour) with the same number, the effect of all other components having incommensurable speeds as well as random noise will be predominantly eliminated. Convenient stencils are available to perform the separation of the various constituents from the current data recorded on proper forms. Each constituent is examined separately, and then the interference effects from other constituents are calculated and used to modify the results. A detailed description of the mechanics of this approach may be found in Schureman, 1941. This method of hand analysis becomes quite laborious and time consuming for all but the shortest of time series, but for over fifty years had been the established method of determining tidal constituents.

The classical approach has been computerized in recent years with

the only major improvement (other than in computing speed) being that successive equally spaced data is multiplied by sines and cosines of angles incremented by the exact angular speed of each constituent, whereas with the hand analysis, successive values are allocated by stencil to the nearest constituent hour and then later corrected for this approximation by the application of suitable augmenting factors.

Another modern technique has now largely been adopted which is known as the least-squares method of tidal analysis. Such an approach utilizes a program which specifies the frequencies of the constituents which are being sought, and the harmonic coefficients of the tidal constituents are then determined simultaneously so that the average values of the residuals squared is a minimum. Correcting the results for node factors or the equilibrium arguments for the starting times remains the same as in the traditional approach.

Comparative tests show that the harmonic constants for the same set of constituents are slightly more accurate utilizing the least-squares method as opposed to the classical approach (Zetler and Lennon, 1967). The greatest advantage in using the least-squares method, however, is that it requires neither equally spaced data nor a synodic period, whereas the traditional Fourier tidal analysis requires both equally spaced data and a quasi-synodic period of the principal constituents (Zetler et al, 1965). In as much as in oceanographic data collection these latter conditions are usually difficult and sometimes impossible to fulfill, the least-squares method of analysis is often the only method which may be used to determine the tidal constituents. The least-squares method has now been adopted by the Coast and Geodetic Survey for the analysis of data series of one year's duration and is

sometimes used with shorter series.

B. TOTAL CURRENT FLUCTUATION FIELD

Over a series of current measurements, the mean value of current speed is given by: $\bar{v} = \sum v / N$

$\bar{v}$ = mean current speed

v = speed at any observation

N = total number of observations

The degree to which numerical data tend to spread about a mean value is termed the variation or dispersion of the data. One measure of the dispersion of the data is the standard deviation, s, which is often termed the root mean square deviation and which is defined by

$$s = \sqrt{\frac{\sum (v - \bar{v})^2}{N}}$$

The variance, which is another method of measuring the spread or dispersion of the variate with reference to the mean, is defined as the square of the deviation or s^2, and the energy of all of the fluctuations of the current over a series of time is equal to the variance. The energy contributed by any periodic component of the fluctuation field is equal to $1/2\ (a_n^2 + b_n^2)$, where a_n and b_n are the Fourier coefficients of any periodic component over the period of investigation. (For derivation, see Appendix A).

Parseval's Theorem tells us that the energy of a composite wave is composed of the sum of the energies of each of the distinct harmonic constituents of the waves of different frequencies making up the basic wave (Ippen, 1966). Thus, from any current fluctuation field, the percentage of total energy due to periodic fluctuations may be calculated and compared to the total energy of all of the fluctuations, and the total energy contributed by individual periodic components may be

determined.

IV. RESULTS

A plot of current velocity versus time for the period 21 November through 17 December 1965 obtained from the General Dynamics Monster Buoy in the Florida Straits was presented in Figure 2. Figure 3 presents a plot of current velocity versus time with a superimposed plot of the predicted tidal component of the current from the results of this analysis. The predicted tidal current is plotted about the mean current (167.05 cm/sec) indicating the predicted Florida Current in the absence of fluctuations of a non-tidal nature. Figure 4 is a plot of the residual after the predicted tidal component of the fluctuations of the Florida Current has been removed. Hourly values for current speed, wind speed and wind direction for the 15 day period are tabulated in Appendix B.

A. DISCUSSION

As can be seen from Figure 2, the second half of the current data series is of much poorer quality than the first half. Gaps in the record were due to telemetry and recording failure. The intense abrupt fluctuations seem to be indicative of a gradual failure of the current meter. Data obtained from the first fifteen days of this period is continuous, and the current meter one minute speed averages were available for each hour.

An initial computer analysis of the entire data series utilizing a least-squares program indicated that the diurnal tidal constituents,

Figure 3. Current Velocity versus Time for the Period 21 November through 5 December 1965 with Superimposed Plot of the Predicted Tidal Modulation.

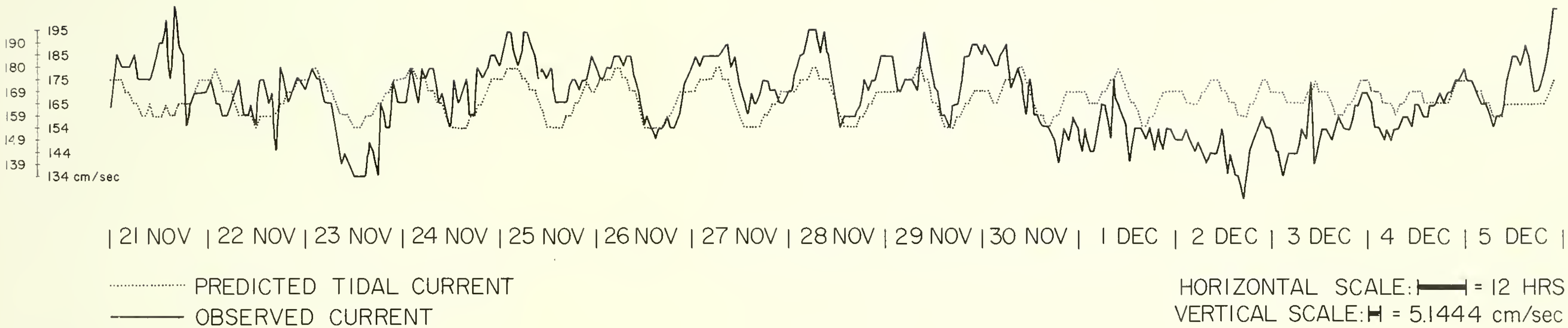

Figure 3. Current Velocity versus Time with Superimposed
Plot of Predicted Tidal Modulation

Figure 4. Plot of the Residual After Tidal Modulation is Removed.

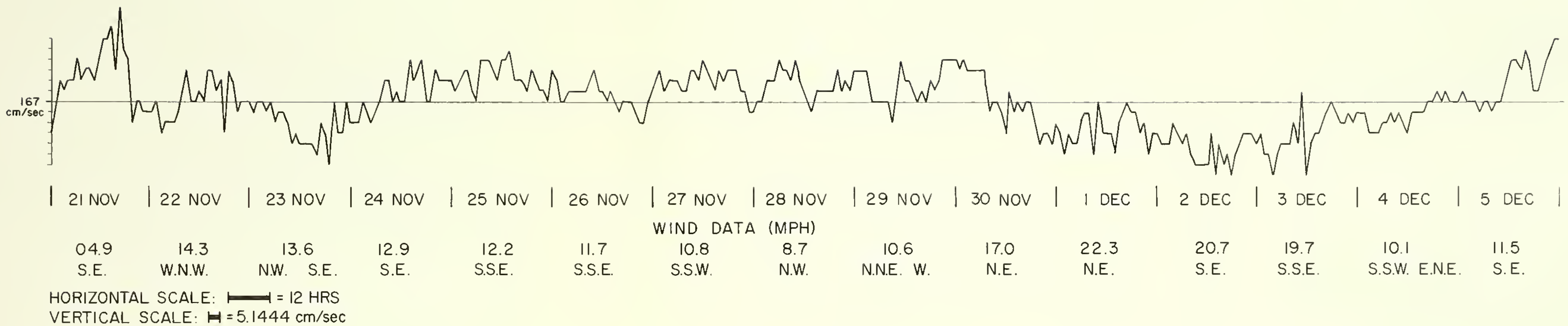

Figure 4. Plot of the Residual After Tidal Modulation is Removed.

Table 2. Comparison of Least-Squares Harmonic Analysis of the First Half of the Data Series with That of the Entire Series.

TABLE 2

Comparison of least-squares harmonic analysis of the first half of the data series with that of the entire series

	K1		O1	
1. 15 DAY ANALYSIS				
(360 Data Entries)	Amplitude*	Phase	Amplitude*	Phase
	0.11	59.8°	0.12	273.5°
2. ENTIRE DATA SERIES	K1		O1	
(596 Data Entries)	0.15	43.5°	0.13	296.5°

* Amplitude is in knots.

Note: Amplitudes and phases are values prior to correcting for equilibrium argument, interference effects, etc. These comparative results will slightly differ from those found elsewhere in this paper as during the above analysis the constituent N_2 was included in the calculations.

K_1 and O_1, are the predominant contributors to the tidal fluctuations of the current. The results of the least-squares analysis for the diurnal constituents for the first fifteen days and the entire period are compared in Table 2. That the phase angles change comparatively little between the two separate analyses is indicative that the amplitudes of the diurnal tidal components are in fact real and not due to random fluctuations. Because the second half of the data series was of marginal reliability, it is not included in the remainder of the analysis.

Table 3 indicates that three techniques for solving for the major tidal constituents produce, as previously discussed, relatively small differences. These differences are accounted for in the method of each technique. The Fourier computer analysis was selected for determining the harmonic constants for the data series. The final results are contained in Table 4. A total of 24 constituents, of which 20 were inferred from the major constituents, were then recombined to produce the predicted tidal modulation of the Florida Current for the period 21 November through 5 December 1965. The predicted plot of tidal modulation is shown superimposed on the basic current data in Figure 3.

Astronomical data for the period is given in Table 5. It can be seen that the predicted tidal modulation is in agreement with the astronomical data for the period. The additive effect of M_2 and S_2 on 22 November is not readily apparent due to the semi-diurnal components being over-shadowed by K_1 and O_1 as they approach phase agreement on 26 November. The predominant diurnal modulation becomes negligible as K_1 and O_1 come into opposition on 3 December leaving only semi-diurnal

Table 3. Comparison of Results of Harmonic Analysis on the First 15 Day Data Period Using Different Analysis Methods.

TABLE 3

Comparison of results of harmonic analysis on the first 15 day data period using different analysis methods

METHOD	M_2		S_2		K_1		O_1	
	Amp*	Phase	Amp*	Phase	Amp*	Phase	Amp*	Phase
1. Hand Analysis	0.063	55.73°	0.048	300.07°	0.125	60.43°	0.103	277.27°
2. Least-Squares Analysis	0.066	57.2°	0.047	301.8°	0.115	59.6°	0.119	274.0°
3. Fourier Computer Analysis	0.063	59.64°	0.047	301.46°	0.132	55.94°	0.106	281.42°

* Amplitude is given in knots.

Note: The amplitudes and phases given are values prior to correcting for equilibrium argument, interference effects, etc.

Table 4. Harmonic Constants from Florida Current Data.

TABLE 4

Harmonic constants from Florida current data

CONSTITUENT**	AMPLITUDE (H) (cm/sec)	KAPPA***
(a.) DIURNAL CONSTITUENTS		
K_1	5.710	24.49°
O_1	5.551	12.25°
P_1	1.888	24.49°
Q_1	1.075	6.13°
J_1	0.437	30.61°
M1	0.396	18.37°
OO_1	0.237	36.74°
RHO_1	0.211	6.98°
$2Q_1$	0.144	0.00°
(b.) OTHER CONSTITUENTS		
M_2	3.400	114.95°
S_2	2.500	309.40°
S_6	1.101	159.88°
K_2	0.679	309.40°
M_6	0.664	277.76°
N_2	0.658	203.68°
S_4	0.458	236.23°
M_4	0.304	41.08°
M_8	0.278	290.55°
T_2	0.149	309.40°
NU_2	0.129	191.79°
L_2	0.098	26.22°
$2N_2$	0.087	292.41°
$LAMBDA_2$	0.026	38.13°
R_2	0.020	309.40°

** Nomenclature and constituent speeds are in accordance with the classical Doodson classification.

*** To convert to Greenwich Epoch (G), add the product of 79.85 times the value of the constituent subscript.

Table 5. Astronomical Data for the Period 21 November Through 17 December 1965.

TABLE 5

Astronomical data for
period 21 November
through 17 December 1965*

22 November	New Moon
26 November	Moon farthest South of Equator
29 November	Moon in apogee
1 December	Moon in First Quarter
3 December	Moon at Equator
8 December	Full Moon
10 December	Moon farthest North of Equator
11 December	Moon in perigee
15 December	Moon in Last Quarter
16 December	Moon at Equator

* From American Ephemeris and Nautical Almanac.

tidal modulation of lesser than usual amplitude as M_2 and S_2 were in phase opposition on 1 December.

Fluctuations of the observed and predicted current are in excellent agreement and clearly show that the tidal modulation is the major periodic fluctuation of the current during the period 23 through 30 November. During the remainder of the data series correlation with the predicted tidal modulation still remains fairly good, but the mean current speed is raised or lowered apparently in response to local wind stress or possibly in response to atmospheric variations over the water regions which are coupled to the Florida Straits.

Figure 4 is a plot of the residual after the predicted tidal modulation has been removed from the data. Included is the mean local wind speed and average wind direction at the buoy location in the Straits during each day from midnight to midnight. It would appear that response of the current to wind stress from either the East or West is negligible, and further that the current fairly rapidly responds with increased velocity to winds from southerly directions. Response of the current to northerly winds appears more complicated with the indication from this limited data series being that the current is slow to initially respond to northerly winds, but once the response commences the current speed is greatly lowered and recovery to normal conditions is quite gradual. The seemingly erratic period, 30 November through 3 December, contained the highest wind speeds and rough seas were prevalent.

Table 6 presents statistical results from the 15 day analysis of the current data. During this period the tidal modulation accounted for 21.35 per cent of the total fluctuations, with the remainder being

Table 6. Statistical Results and Energy Calculations for the 15 Day Period.

TABLE 6

Statistical results and energy calculations for the 15 day period

1.	Mean Current Velocity	167.05 cm/sec
2	Standard Deviation	15.42 cm/sec
3.	Average Fluctuation	9.23 per cent
4.	Total Current Variance.	237.90 cm^2/sec^2
5.	Predicted Tidal Current Variance.	50.79 cm^2/sec^2
6.	Fluctuations Due to Tidal Components.	21.35 per cent
7.	Percent of Item 6 Due to Major Diurnal Tidal Components (K_1 and O_1)	71 per cent
8.	Percent of Item 6 Due to Major Semi-Diurnal Tidal Components (M_2 and S_2)	20 per cent
9.	Energy Contributed by Individual Tidal Constituents (cm^2/sec^2)	
	K_1	16.30
	O_1	15.40
	M_2	5.78
	S_2	3.12
	P_1	1.78
	S_6	0.60
	Q_1	0.58
	Remainder Semi-Diurnal Constituents.	0.88
	Remainder Diurnal Constituents . . .	0.24

[illegible]

[illegible]

fluctuations of an apparent non-periodic nature.

B. COMPARISON OF RESULTS

The analysis of the surface current data reveals large diurnal tidal modulation of the Florida Current. This is in agreement with the tidal analysis performed on the transport of the Florida Current by Richardson and Schmitz (*op. cit.*), and tidal analysis of transport fluctuations from studies of electric potential measurements by Wertheim (*op cit.*). It is further in agreement with Project MIMI's results where underwater acoustic signals transmitted across the Straits of Florida over long periods of time have shown prominent diurnal phase changes. (Steinberg and Birdsall, 1966), (Clark and Yarnall, 1967).

Recently Zetler calculated the amplitude of the K_1 tidal current in the Florida Straits required to conform to observations of the oscillating diurnal tidal water transport in the Gulf of Mexico (Zetler, 1968). The K_1 amplitude of 0.11 knots found from the harmonic analysis of the Monster Buoy data is in remarkable close agreement to his calculated value of 0.12 knots.

The following is a comparison of the phase angles of the major diurnal constituents of the tidal current with the phase angles for the tide at the Patrick Air Force Base and Miami Beach shore stations. No harmonic constants are available for tide at the Monster Buoy latitude.

TIDE LOCATION	LATITUDE	PHASE (° G)	
		K_1	O_1
Patrick AFB	28°14' N	203	207
Miami Beach	25°46' N	245	267
TIDAL CURRENT			
Monster Buoy	26°01' N	284	272

If a wave is progressive, the difference in phase between tidal current and the resultant tide should be zero degrees at any location, whereas in a standing wave situation there should be a 90° difference. As can be seen, the differences found were inconsistent and probably indicate some combination of both a progressive and standing wave. Since, cotidal lines bunch up near a node and tidal constants at the latitude of the current observations are not available, the above comparison is of marginal suitability. No analysis of tidal currents at any of the shore stations is available for comparison.

Zetler (1968) concluded, after consideration of the available known K_1 and O_1 phase angles at shore stations along either side of the Straits of Florida, that there is a strong indication of a longitudinal standing wave situation for the major diurnal tidal components in the Straits of Florida, with a node close to the latitude of Miami. The large amplitudes of the diurnal constituents of the tidal modulation of the Florida Current at the Hollywood latitude are in agreement with this concept as the tidal current related to this wave should be maximum at the node.

V. SUMMARY AND CONCLUSIONS

During the latter portion of 1965 direct surface current measurements of the Florida Current were taken at hourly intervals over an approximate period of one month from the General Dynamics Monster Buoy anchored in the Straits of Florida at the Hollywood latitude. The data from this period presented the opportunity of conducting the first Florida Current tidal analysis from direct surface current measurements of sufficient duration to provide meaningful results.

Harmonic analysis of data from 15 complete days of this period confirms that the resultant tidal influence on the Florida Current surface flow does not conform to the usual Atlantic coastal tidal configuration, being instead transitional between the semi-diurnal Atlantic tide and the diurnal Gulf of Mexico tide. The tidal coupling between the Gulf of Mexico and the Atlantic Ocean with pronounced diurnal features can only at present be explained by a heretofore overlooked longitudinal diurnal standing wave in the Florida Straits. The obtainment and subsequent analysis of tide observations at additional points along the lower third of the east coast of Florida should confirm the presence of this diurnal standing wave.

A fluctuation of 10 per cent of the mean surface current is given as representative of the Florida Current. Slightly more than one-fifth of this modulation is attributed to tidal influence, being the apparent major periodic modulating force of the Florida Current.

It is recommended that further work be continued in this field.

The obtainment of tidal current data in the Straits of Florida from a deep subsurface buoy would be particularly invaluable for analysis. Additionally, the placement of another data gathering platform in the Florida Current at about the Miami latitude for long term fluctuation study of the Florida Current would be well worth the expense.

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APPENDIX A:

DERIVATION OF THE ENERGY FORMULA OF A HARMONIC TIDAL COMPONENT

If any harmonic component of the mean current speed is represented by: $v = a_n \mathrm{Sin}wt + b_n \mathrm{COS}wt$

where $w = \frac{2\pi}{T}$ is the angular speed of the motion, then the energy of the periodic motion may be represented by:

$$P.E. + K.E. = \frac{1}{T}\int_0^T v^2 dt$$

$$= \frac{1}{T}\int_0^T a_n^2 \mathrm{Sin}^2 wtdt + \frac{1}{T}\int_0^T b_n^2 \mathrm{COS}^2 wtdt + \frac{1}{T}\int_0^T a_n b_b \mathrm{Sin}wt\mathrm{COS}wtdt$$

$$= \frac{a_n^2}{T}\left[\frac{t}{2} - \frac{\mathrm{Sin}2wt}{4w}\right]_0^T + \frac{b_n^2}{T}\left[\frac{t}{2} + \frac{\mathrm{Sin}2wt}{4w}\right]_0^T + \frac{a_n b_n}{T}\left[\frac{1}{2w}\mathrm{Sin}^2 wt\right]_0^T$$

$$= \frac{a_n^2}{2} + \frac{b_n^2}{2} - \frac{a_n^2 \mathrm{Sin}2wT}{8wT} + \frac{b_n^2 \mathrm{Sin}2wT}{8wt} + \frac{a_n b_n \mathrm{Sin}^2 wT}{4wT}$$

$$= \frac{1}{2}(a_n^2 + b_n^2) - \frac{(a_n^2 - b_n^2)}{8wt}(\mathrm{Sin}2wt) + \frac{(a_n b_n)}{(4wt)}\mathrm{Sin}^2 wt$$

$$= \frac{1}{2}(a_n^2 + b_n^2) - \frac{(a_n^2 - b_n^2)}{(8)\left(\frac{2\pi}{T}\right)(T)}\left[\mathrm{Sin}\,2\left(\frac{2\pi}{T}\right)T\right] + \frac{(a_n b_n)}{(4)\left(\frac{2\pi}{T}\right)(T)}\mathrm{Sin}^2\left(\frac{2\pi}{T}\right)(T)$$

$$= \frac{1}{2}(a_n^2 + b_n^2)$$

APPENDIX B:

FLORIDA CURRENT DATA

AND

ENVIRONMENTAL DATA FOR

THE 15 DAY PERIOD

DATE	TIME (LOCAL)	CURRENT SPEED (kts)	WIND SPEED (mph)	WIND DIRECTION
11/21/65	0000	3.1	7	120°
"	0113	3.4	6	135°
"	0203	3.6	4	120°
"	0258	3.5	1	130°
"	0401	3.5	3	120°
"	0500	3.5	4	100°
"	0600	3.6	7	100°
"	0657	3.4	9	110°
"	0800	3.4	10	100°
"	0902	3.4	4	120°
"	1000	3.4	4	100°
"	1100	3.5	5	120°
"	1200	3.7	2	145°
"	1300	3.7	2	120°
"	1400	3.9	2	200°
"	1503	3.4	3	200°
"	1600	4.0	4	180°
"	1700	3.7	3	190°
"	1800	3.6	3	190°
"	1900	3.0	4	220°
"	2001	3.2	9	200°
"	2110	3.3	8	200°
"	2206	3.3	8	220°
"	2303	3.3	10	220°
11/22/65	0002	3.3	11	240°
"	0101	3.4	11	250°
"	0206	3.2	17	240°
"	0301	3.2	17	240°
"	0401	3.1	6	250°
"	0502	3.1	16	260°
"	0604	3.2	14	270°
"	0702	3.3	12	250°
"	0800	3.4	10	300°
"	0920	3.1	12	260°
"	1000	3.1	14	280°
"	1100	3.2	10	290°
"	1200	3.0	13	260°
"	1301	3.4	13	260°
"	1400	3.4	13	272°
"	1500	3.2	14	270°
"	1600	3.3	17	325°
"	1700	2.8	18	300°
"	1800	3.5	19	310°
"	1900	3.4	21	325°
"	2002	3.2	22	330°
"	2104	3.3	16	330°
"	2204	3.4	12	330°
"	2303	3.4	15	325°

DATE	TIME (LOCAL)	CURRENT SPEED (kts)	WIND SPEED (mph)	WIND DIRECTION
11/23/65	0000	3.3	12	330°
"	0100	3.4	15	320°
"	0200	3.5	19	320°
"	0259	3.4	20	320°
"	0402	3.4	18	320°
"	0500	3.2	19	320°
"	0603	3.2	20	335°
"	0700	3.2	20	340°
"	0800	3.0	15	340°
"	0900	2.7	12	020°
"	1000	2.8	12	040°
"	1100	2.7	12	030°
"	1200	2.6	11	060°
"	1300	2.6	12	060°
"	1400	2.6	10	060°
"	1500	2.6	5	070°
"	1600	2.9	8	070°
"	1701	2.8	8	080°
"	1800	2.6	10	068°
"	1900	3.2	16	110°
"	2001	3.0	14	130°
"	2100	3.0	17	130°
"	2200	3.4	13	130°
"	2302	3.2	10	120°
11/24/65	0002	3.2	13	110°
"	0110	3.2	17	120°
"	0220	3.5	11	120°
"	0300	3.4	10	120°
"	0400	3.2	12	120°
"	0500	3.5	15	120°
"	0558	3.4	15	120°
"	0700	3.5	13	115°
"	0800	3.5	12	140°
"	0900	3.2	10	140°
"	1000	3.3	11	140°
"	1100	3.1	12	135°
"	1203	3.0	15	132°
"	1300	3.4	12	140°
"	1400	3.2	13	135°
"	1500	3.3	10	120°
"	1600	3.4	11	140°
"	1700	3.1	15	140°
"	1800	3.1	15	140°
"	1900	3.5	16	140°
"	2003	3.4	14	150°
"	2104	3.5	10	150°
"	2202	3.6	10	120°
"	2304	3.6	15	180°

DATE	TIME (LOCAL)	CURRENT SPEED (kts)	WIND SPEED (mph)	WIND DIRECTION
11/25/65	0000	3.5	20	170°
"	0100	3.6	18	180°
"	0201	3.8	18	180°
"	0300	3.8	20	180°
"	0400	3.6	19	200°
"	0458	3.5	18	180°
"	0600	3.8	14	200°
"	0701	3.8	15	200°
"	0800	3.7	15	188°
"	0900	3.6	10	140°
"	1000	3.4	16	060°
"	1100	3.5	20	135°
"	1200	3.4	1	060°
"	1300	3.5	7	200°
"	1400	3.2	4	060°
"	1500	3.2	5	060°
"	1600	3.2	5	075°
"	1700	3.2	9	120°
"	1800	3.4	10	160°
"	1900	3.4	9	140°
"	2001	3.3	12	160°
"	2100	3.4	9	130°
"	2201	3.4	12	150°
"	2300	3.6	10	150°
11/26/65	0000	3.5	12	170°
"	0103	3.4	10	150°
"	0200	3.4	8	180°
"	0301	3.5	7	180°
"	0401	3.5	10	175°
"	0501	3.6	6	160°
"	0605	3.6	6	160°
"	0700	3.5	9	140°
"	1800	3.6	7	135°
"	0900	3.6	7	140°
"	1000	3.4	10	150°
"	1100	3.3	9	140°
"	1200	3.0	10	140°
"	1300	3.1	9	130°
"	1400	3.0	14	140°
"	1500	2.9	15	140°
"	1600	3.0	12	170°
"	1700	3.0	12	170°
"	1800	3.1	18	160°
"	1857	3.0	19	175°
"	2000	3.0	17	145°
"	2100	3.1	18	180°
"	2200	3.3	16	180°
"	2257	3.4	20	180°

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

DATE	TIME (LOCAL)	CURRENT SPEED (kts)	WIND SPEED (mph)	WIND DIRECTION
11/27/65	0000	3.5	20	190°
"	0058	3.6	18	190°
"	0200	3.5	18	190°
"	0300	3.6	19	220°
"	0403	3.6	12	210°
"	0505	3.6	12	190°
"	0615	3.6	12	170°
"	1700	3.6	5	170°
"	0810	3.7	9	200°
"	0900	3.7	10	180°
"	1000	3.5	10	160°
"	1100	3.6	15	170°
"	1200	3.4	12	185°
"	1300	3.2	14	185°
"	1400	3.1	10	200°
"	1500	3.3	6	220°
"	1600	3.2	4	200°
"	1700	3.3	7	200°
"	1800	3.4	7	215°
"	1900	3.4	8	200°
"	2000	3.3	8	200°
"	2100	3.3	8	210°
"	2200	3.2	8	210°
"	2300	3.2	8	230°
11/28/65	0000	3.3	9	250°
"	0100	3.3	9	270°
"	0200	3.5	10	280°
"	0300	3.6	10	330°
"	0400	3.6	10	340°
"	0500	3.8	11	340°
"	0600	3.8	11	340°
"	0700	3.8	10	345°
"	0800	3.6	10	340°
"	0900	3.8	10	340°
"	1000	3.6	10	350°
"	1100	3.4	9	345°
"	1200	3.2	8	330°
"	1300	3.0	5	340°
"	1400	3.1	3	268°
"	1500	3.1	3	280°
"	1600	3.1	4	270°
"	1700	3.1	6	275°
"	1800	3.2	8	280°
"	1900	3.4	10	260°
"	2000	3.3	7	280°
"	2100	3.4	8	300°
"	2200	3.4	12	320°
"	2300	3.6	16	340°

DATE	TIME (LOCAL)	CURRENT SPEED (kts)	WIND SPEED (mph)	WIND DIRECTION
11/29/65	0000	3.6	13	040°
"	0100	3.6	14	010°
"	0200	3.6	12	000°
"	0300	3.3	10	350°
"	0400	3.3	11	350°
"	0500	3.4	13	000°
"	0600	3.4	12	000°
"	0700	3.4	13	350°
"	0800	3.3	15	010°
"	0900	3.6	11	020°
"	1000	3.8	10	000°
"	1100	3.6	10	020°
"	1200	3.4	9	020°
"	1300	3.3	5	020°
"	1400	3.1	3	150°
"	1500	3.1	5	220°
"	1600	3.0	9	255°
"	1700	3.2	5	240°
"	1800	3.2	8	275°
"	1900	3.3	10	280°
"	2000	3.6	12	280°
"	2100	3.6	12	280
"	2200	3.7	15	290°
"	2300	3.7	18	300°
11/30/65	0000	3.6	15	310°
"	0100	3.7	12	320°
"	0200	3.6	12	320°
"	0300	3.5	10	000°
"	0400	3.5	15	030°
"	0500	3.6	14	059°
"	0600	3.7	11	060°
"	0700	3.3	17	030°
"	0800	3.4	19	035°
"	0900	3.5	19	350°
"	1000	3.4	18	000°
"	1100	3.1	14	005°
"	1200	3.4	12	000°
"	1300	3.1	20	350°
"	1400	3.1	22	050°
"	1500	3.0	21	050°
"	1600	3.0	20	060°
"	1700	3.0	20	050°
"	1800	2.9	18	060°
"	1900	2.7	17	060°
"	2000	2.9	21	060°
"	2100	3.0	20	060°
"	2200	2.9	20	060°
"	2300	3.1	22	050°

DATE	TIME (LOCAL)	CURRENT SPEED (kts)	WIND SPEED (mph)	WIND DIRECTION
12/1/65	0000	3.0	22	050°
"	0100	2.8	25	060°
"	0200	3.0	24	040°
"	0300	2.8	25	058°
"	0400	2.8	25	058°
"	0500	3.0	25	058°
"	0600	3.2	27	056°
"	0700	3.2	27	055°
"	0800	2.9	22	058°
"	0900	3.4	25	060°
"	1000	3.2	22	060°
"	1100	3.1	20	060°
"	1200	3.0	21	060°
"	1300	2.7	20	060°
"	1400	3.0	20	060°
"	1500	3.0	19	060°
"	1600	3.0	20	080°
"	1700	2.9	16	100°
"	1800	3.0	20	100°
"	1900	2.8	20	090°
"	2000	3.0	26	110°
"	2100	2.8	22	120°
"	2200	3.0	22	110°
"	2300	3.0	20	120°
12/2/65	0005	2.9	25	110°
"	0100	2.9	26	120°
"	0200	2.9	22	140°
"	0300	3.0	20	110°
"	0400	2.9	20	110°
"	0507	2.8	25	125°
"	0602	2.9	22	125°
"	0701	2.8	20	140°
"	0800	2.7	25	130°
"	0900	2.8	20	140°
"	1000	2.8	25	160°
"	1100	2.8	19	150°
"	1200	3.0	20	150°
"	1300	2.6	19	160°
"	1400	2.8	20	150°
"	1500	2.6	16	150°
"	1600	2.6	19	160°
"	1700	2.4	18	180°
"	1800	2.6	15	180°
"	1900	2.8	20	180°
"	2000	2.9	18	160°
"	2100	3.0	20	180°
"	2200	3.1	20	190°
"	2300	3.0	22	160°

DATE	TIME (LOCAL)	CURRENT SPEED (kts)	WIND SPEED (mph)	WIND DIRECTION
12/3/65	0000	3.0	22	160°
"	0100	2.8	20	150°
"	0200	2.8	20	140°
"	0300	2.6	24	170°
"	0400	2.7	22	190°
"	0500	2.8	19	180°
"	0600	2.8	15	150°
"	0800	2.8	14	150°
"	0800	3.0	20	160°
"	0900	2.9	22	160°
"	1000	3.4	25	170°
"	1100	2.7	25	170°
"	1200	2.9	25	160°
"	1300	3.0	20	180°
"	1400	3.0	21	185°
"	1500	2.9	20	180°
"	1600	3.0	20	185°
"	1700	3.1	18	180°
"	1800	3.0	18	180°
"	1900	3.0	18	175°
"	2000	3.0	18	190°
"	2100	3.2	14	190°
"	2200	3.2	16	190°
"	2300	3.3	16	185°
12/4/65	0000	3.3	15	200°
"	0100	3.2	13	200°
"	0200	3.0	9	200°
"	0300	3.0	8	200°
"	0400	2.9	8	200°
"	0500	3.0	8	200°
"	0600	3.0	12	200°
"	0700	3.0	10	200°
"	0800	3.0	11	180°
"	0900	3.1	12	200°
"	1000	3.1	9	190°
"	1100	3.0	8	220°
"	1200	3.2	5	240°
"	1300	3.2	5	220°
"	1400	3.1	7	230°
"	1500	3.1	7	240°
"	1600	3.2	4	240°
"	1700	3.2	3	280°
"	1800	3.3	4	000°
"	1900	3.2	20	065°
"	2000	3.3	16	060°
"	2100	3.3	15	070°
"	2200	3.4	15	060°
"	2300	3.4	18	060°

DATE	TIME (LOCAL)	CURRENT SPEED (kts)	WIND SPEED (mph)	WIND DIRECTION
12/5/65	0000	3.5	18	080°
"	0051	3.4	15	100°
"	0200	3.4	18	090°
"	0300	3.3	15	090°
"	0400	3.2	15	060°
"	0500	3.2	12	125°
"	0600	3.2	13	100°
"	0700	3.0	17	059°
"	0800	3.1	12	080°
"	0900	3.1	16	058°
"	1000	3.3	12	060°
"	1100	3.5	11	060°
"	1200	3.6	8	150°
"	1300	3.6	12	130°
"	1400	3.5	11	120°
"	1500	3.7	12	150°
"	1600	3.6	10	225°
"	1700	3.3	10	165°
"	1800	3.3	6	200°
"	1900	3.4	8	180°
"	2000	3.6	5	170°
"	2100	3.8	6	275°
"	2200	4.0	9	120°
"	2300	4.0	5	195°

VITA

Lt. John Alan Smith, USN, was born in Norwood, Massachusetts, on December 5, 1937. His parents were Arthur L. Smith and Elinor Smith. He received his elementary education in the Walpole public school system at Walpole, Massachusetts, and his secondary education at Fort Lauderdale High School, Fort Lauderdale, Florida.

In September 1955, he enlisted in the United States Navy, and served in the USS NAUTILUS (SSN571) and attended the U.S. Naval Academy Preparatory School at Bainbridge, Maryland from September 1956 to June 1957. In July, 1957, he entered the U.S. Naval Academy, Annapolis, Maryland. Upon graduation in June, 1961, with a B.S., he was commissioned an Ensign in the U.S. Navy. Subsequent Naval Service included five years in the Destroyer Force of the Atlantic Fleet with attendance at Fleet ASW School at Key West, Florida, and Fleet Destroyer School at Newport, Rhode Island.

He was admitted to the Graduate School of the University of Miami in September, 1966. He was granted the degree of Master of Science in July, 1968

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